A STATISTICAL ANALYSIS OF SUMMER STRATUS OVER SOUTH TEXAS

By MARION E. CRAWFORD

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During a study which was begun in an attempt to form a clearer conception of the processes involved in the formation and dissipation of stratus clouds in south Texas some interesting observations were made and are here presented, in the hope that some of the precepts derived will be of use in forecasting the behavior of the stratus cloud.

This study is necessarily based on data available at San Antonio, Tex., which consist chiefly of airplane soundings made at Kelly Field during the summer seasons of 1934–36, inclusive.

During the summer, when the stratus is most common, the normal pressure distribution is such that a slow steady flow of Tropical air which originated in the Trade-wind zone is fed into the eastern and central United States (**1**). In Texas the invasion of summer Tropical Atlantic (TA) air is sometimes shallow, probably about 1 km, and is overlaid with dry superior (S) air. Although cooling by radiation is somewhat limited by the high moisture content (16 to 18 g/kg at the surface) of TA air, the diurnal temperature range is about 20° F. The surface air is, therefore, usually cooled to within a few degrees of its dew point by morning. This condition associated with a moderate southeasterly wind quite often results in the rapid formation of stratus clouds during the night. Usually the sky is clear prior to the formation of the stratus, which first makes its appearance in thin scattered sheets that gradually thicken into a solid cloud layer with a uniform ceiling. The complete process, from clear to overcast, has frequently been observed to take place within a 5-minute period. Almost invariably a ceiling is left under the stratus deck, seldom if ever decreasing below 400 feet; in addition, visibility is always good under the stratus as ground fog has never been observed to occur with the summer stratus, so that, in general, aviation difficulties are only moderate. The height of the stratus is usually between 500 and 2,000 feet, varying in thickness from less than 100 to more than 1,000 feet. This uniform layer obtains until after sunrise when it begins to break up, usually resulting in cumulus by noon. Almost invariably this condition occurs unaccompanied by precipitation, fog, or thunderstorms.

During the summer, when the cloud occurs, there is no appreciable change in the weather from day to day, and little change in the specific humidity; thus, eliminating any possibility of it being a frontal or transitional condition. The stratus forms entirely within the moist stratum, usually just below the inversion. The surface of discontinuity between the TA and S air is manifested by a small temperature inversion accompanied by a sharp decrease in specific humidity. Since the occurrence of the so-called "Gulf clouds" or stratus is always associated with a southeasterly wind up to and through the moist stratum, the air is obviously of gulf origin.

Because of the uniform warmth of the waters in the TA source region, the air mass is very moist and quite warm. The conditional equilibrium and high relative humidity observed through the very moist stratum are such that comparatively little forced ascent of the warm current is necessary to bring about a more unstable condition that eventually leads to condensation and cloud formation. This cooling by lifting of the lower strata of air is usually not enough to produce precipitation during the summer. Consequently the prevailing weather conditions in the TA air masses are those of warmth and high humidity accompanied by a good deal of cloudiness during the night and early morning. Visibility is always good under the stratus.

TABLE 1.—*Summary of airplane soundings through the moist stratum and to the top of the overlying temperature inversion during June, July, and August 1934–36, inclusive*

Amount of low clouds at time of take-off	Number of observations	Surface (206 m M. S. L.)				Base of moist stratum						Top of moist stratum						Top of inversion					Refer. to curve in figure
		T (°C)	q (g/kg)	R. H. (%)	θ_E (°A)	Altitude m (M. S. L.)	T (°C)	q (g/kg)	R. H. (%)	θ_E (°A)	Lapse Rate	Altitude (M. S. L.)	T (°C)	q (g/kg)	R. H. (%)	θ_E (°A)	Lapse rate	Altitude (M. S. L.)	T (°C)	q (g/kg)	R. H. (%)	θ_E (°A)	
Clear	96	22.7	16.0	91	342	491	23.9	16.3	84	348	+.42	733	22.5	16.0	87	348	−.58	1,014	22.8	11.8	61	340	I
Scattered	33	23.3	16.8	92	345	617	22.6	17.0	93	350	−.17	790	21.5	16.6	95	349	−.64	1,141	21.3	12.0	67	340	II
Broken to overcast	82	24.1	17.8	93	348	560	22.9	17.6	95	351	−.34	877	20.8	16.2	96	348	−.66	1,185	21.4	11.2	62	338	III

The summarized data consist of airplane soundings made during the months of June, July, and August 1934–36, inclusive. Only those observations on days when a moist stratum was present at lower levels, and on which the stratum broke up during the day, were considered. The grouping under the headings of clear, scattered, and broken to overcast, refers to the amount of low clouds present at the time of take-off. Intermediate and high clouds were not considered in this grouping. The accompanying figure shows the temperature and specific humidity data plotted against height.

In consideration of the summarized data and other data at hand, several points are found worthy of enumeration.

1. The temperature lapse rate in the moist stratum, whether clear, scattered, or broken to overcast conditions prevail, lies between 0.58° and 0.66° C. per 100 meters, a value greater than the saturation adiabatic rate which is approximately 0.40° C. for the high temperatures involved. The moist stratum is, therefore, in conditional equilibrium. The condition is simply that the layer is unstable if saturated, but stable if unsaturated (**2**). The high relative humidity of the stratum indicates that very little forced ascent is necessary to produce saturation, resulting in instability with respect to saturated air.

2. When the sky is clear of stratus and remains so until after sunrise, even though a moist stratum is present aloft, a ground inversion is usually present indicating very little air movement. This in turn indicates the absence of mechanical turbulence, and hence a clear night.

3. As soon as the air movement increases slightly, the dynamic turbulence prevents the formation of a marked ground inversion; the cooling effect being distributed more rapidly upward. As the air movement becomes stronger, mechanical turbulence is increased and maintains a thoroughly mixed stratum of air at the ground, topped by a stratus deck.

4. The difference between the temperatures at the base and at the top of the moist stratum for the three conditions is due to adiabatic changes.

5. The moisture distribution is typical of a turbulent layer; that is, the specific humidity is nearly constant at a high value up to the base of the inversion, where it decreases sharply.

6. The relative humidity is high throughout the moist stratum, reaching a maximum at the base of the inversion.

7. As the normal air current of the Texas coast in summer is from the southeast, it might well be expected that the temperature at the base of the moist stratum, approximately 600 *m* M. S. L., to be 23° or 24° C. as the result of adiabatic change in temperature with elevation, because the sea-surface temperatures during the warmest season average over the entire Gulf of Mexico and the Caribbean Sea region close to 28° or 29° C.

8. That radiational cooling which occurs near the upper surface of the moist stratum is not the predominating factor in the formation of the stratus is evident as no pronounced cooling takes place at the upper surface of the moist stratum to cause instability with respect to dry air, leading to the formation of the stratus by a convective process. There is very little steepening of the lapse rate through the moist stratum after the stratus forms. This should not be interpreted to mean that radiation does not play a part. Perhaps occasionally, in individual soundings where the lapse rate in the moist stratum was very near the dry adiabatic rate before the stratus formed, it is the predominating factor (**3**); but generally such a steep lapse rate does not prevail.

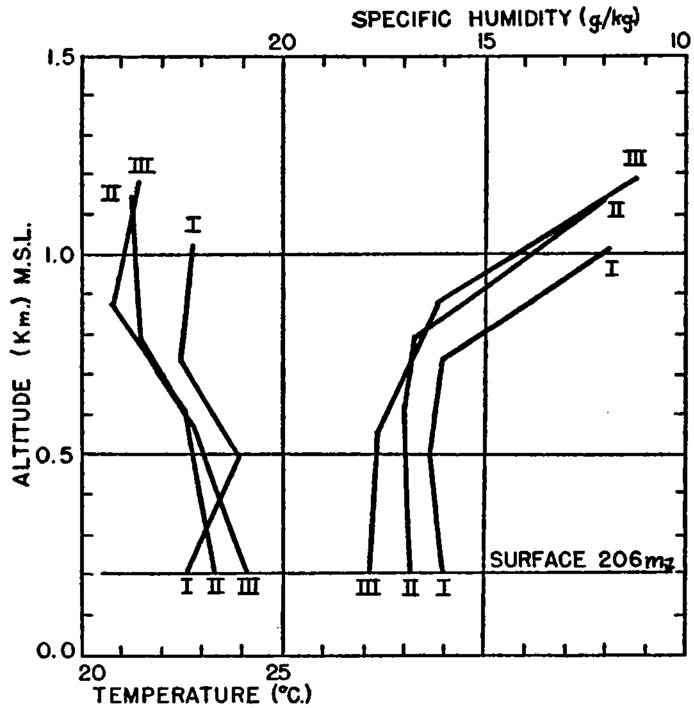
9. It was noted that, when the sky is clear of stratus, the saturation level of the base of the moist stratum is above the base of the inversion. Scattered stratus is present when the saturation level is at or very near the base of the inversion; the amount of the scattered stratus is usually quite variable. With broken to overcast stratus the saturation level of the base of the moist stratum is considerably below the base of the inversion.

10. All soundings in which the stratus is present are characterized by an overlying dryer and warmer air. The very stable layer of air separating the two strata acts as a lid through which little mixing of air takes place; and, also, the turbulence, produced by the surface over which the air current is passing, usually ceases near this height. This leads to the somewhat paradoxical statement that the drier the overlying air the greater the probability of stratus, provided, of course, that there is an extremely moist stratum of air next to the ground.

Thus, a logical explanation of the inversion should precede that of the stratus formation. Since in Texas the invasion of summer TA air usually occurs with dry S air aloft, the presence of a small temperature inversion between the two air strata is to be expected as the S air averages a few degrees higher than TA at intermediate levels. Occasionally this inversion is strengthened by extremely warm S air aloft. It is also slightly intensified at night by the outgoing radiation from the top of the moist stratum.

When the S air is replaced by TA air, no inversion is present to limit the distribution of the terrestrial radiational cooling; and it is therefore carried to upper levels, resulting in a more moderate lapse rate through the extremely moist stratum. Consequently the probability of stratus is lessened as conditional equilibrium is not likely to occur in the lower levels, because of thermal stability in the air mass.

Returning to the effect of the inversion: it is found that when the saturation point is reached and stratus forms under the inversion, the outgoing radiation at night from the upper surface of the cloud layer will be that of a "black" body, and will follow the well-known Stefan's law $R=cT^4$ where c is a constant characteristic of a black body, T the absolute temperature, and R the radiation (**4**). But the outgoing radiation from the warmer and drier air immediately above the cloud layer will be that of a "gray" body. The radiation from moist air R′ depends largely on the amount of water vapor present according to Brunt (**5**). The lapse rate through the moist stratum indicates that no pronounced cooling takes place at the top of the moist stratum after the stratus forms, as it is not appreciably steeper with an overcast than when the sky is clear of stratus (figure 1).



The conclusion is reached that the temperature inversion is due to the surface of discontinuity between TA and S air, strengthened slightly by radiation from the upper surface of the moist stratum.

This satisfactorily explains the presence of the early morning temperature inversion above the moist stratum and its relatively small magnitude, but not the formation of the stratus.

Notwithstanding the fact that a minimum of cloudiness occurs simultaneously with a maximum of wind (surface) movement, and vice versa (**6**), the theory is supported that mechanical turbulence is the predominant factor in producing the cloud. It is not so well known that the maximum wind movement during the early morning hours is ordinarily found at an elevation of from 400 to 600 meters above the surface (**7**), i. e., 600 to 800 M. S. L. at San Antonio. This (gradient) wind is usually over twice the velocity of the surface wind. Therefore, mechanical turbulence must be present at night when there is a rapid increase in wind velocity with elevation. In the absence of much wind movement mechanical turbulence is proportionately lessened. The turbulence is not always sufficiently strong to be termed as such by pilots, but is active enough to keep a thoroughly mixed stratum of air near the ground.

In addition to increasing the turbulent motion the stronger southeasterly wind brings in air of higher specific humidity from the Gulf, along with a faster rate of cooling caused by forced ascent up the coastal slope.

Since the very moist stratum of air is present much of the time regardless of whether or not stratus forms, the necessary factor, i. e., mechanical turbulence, for its formation is supplied by an increased wind movement, especially just above the surface. As the lapse rate through the moist stratum lies between the dry and saturation adiabatic rates, an element lifted upward will first encounter resistance to its vertical motion, because it would cool with altitude at the faster dry adiabatic rate; after condensation it would follow the saturation adiabatic rate, which is slower than that of the surrounding atmosphere, and pass from stable to unstable at the equilibrium level, after which it would continue to rise to the base of the inversion because it would then be lighter than its environment. This results in the formation of the observed uniform layer of stratus clouds. This type of temperature distribution (through the moist stratum) is called convective instability, the conditions being (a) a sufficient amount of moisture in the air so that the moving element becomes saturated soon enough to follow a saturation adiabatic line which intersects the prevailing lapse rate curve, and (b) a strong enough mechanically-produced lifting to overcome the stabilizing forces at the lower levels and carry the element to the equilibrium point (**8**).

Convective instability is also definitely indicated as the equivalent potential temperature decreases with height within the layer.

The influence of nocturnal radiation is evident because the stratus forms at night. The principal cooling seems to take place by terrestrial radiation and, in the absence of a moderate air movement, causes a ground inversion. Therefore, when a marked ground inversion is present, no stratus forms because of the lack of turbulence. Other factors indicated in the summarized data are much the same as when stratus is present; but mechanical turbulence is evidently absent as it would prevent the formation of the ground inversion.

As soon as there is the slightest air movement, the dynamic turbulence prevents the formation of a marked ground inversion; the cooling effect being distributed more rapidly upward (**9**). As soon as the air movement becomes stronger, the dispersion of the air cooled near the ground becomes such that ground inversions can no longer exist. The condition that prevents or eradicates ground inversions, therefore, facilitates the formation of stratus. Consequently the two conditions, i. e., a marked ground inversion and a stratus deck, are seldom observed in the same sounding. It should be noted that the upper inversion is present even when the sky is clear and conditions are calm, and is not the result of the ground inversion being forced upward as the wind velocity increases.

Although no summary of soundings is available for proof, it seems logical to assume that the breaking up of the stratus into cumulus is by convective turbulence brought about by a steeper lapse rate near the ground caused by insolational heating of the air near the ground during the daytime as it moves inland from the Gulf coast. As previously stated, in Texas the invasion of summer TA accompanied by dry S air aloft makes thunderstorms in TA air much less likely than farther east; the decrease in equivalent potential temperature aloft indicates much potential instability but in the absence of much moisture it cannot be realized very often except from the marked vertical displacement with passage of cold fronts. Thus, only cumulus results from the stratus with a tendency to dissipate in the early afternoon. Complete dissolution, of course, depends on the dryness of the overlying S air.

Unfortunately, upper air wind velocity data were not readily available for correlation with the airplane soundings.

Summary.—Investigations of the South Texas stratus by means of airplane soundings at San Antonio, Texas showed that the lapse rate through the moist stratum of air which produces the stratus lies between the dry and the saturation adiabatic rates, and it is overlaid with a drier and warmer air mass (S) separated by a small inversion. Nocturnal radiation cools the lower layers of air and brings about a more nearly saturated condition near the ground. When the moist stratum remains free of stratus, a marked ground inversion is present, indicating little air movement and, thus, the lack of turbulence. The presence of a pressure distribution favorable for the establishment of a comparatively strong southeasterly gradient wind not only brings in air of higher moisture content; but, also, produces the necessary mechanical turbulence for the formation of stratus. During the night, when the air movement increases sharply with elevation, turbulence should be expected. Mechanical turbulence is apparently the predominating factor in the formation of the stratus as it is apparently the only significant factor present in the stratus formation which is absent when the sky remains clear.

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